Power Minimization in Dual-Hop Underlay Cooperative Cognitive Radio Relay Networks for Optimal Resource Allocation

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Abstract- In this paper, we investigate a multi-user one-way dual-hop multi-relay cognitive radio underlay spectrum sharing network. The joint optimal resource allocation of the bandwidth and power allocation in underlay Cooperative Cognitive Radio Relay Network (CCRRN) was studied and a convex optimization analytical framework is presented. A combined optimal power and bandwidth allocation (COPBA) scheme for the minimization of the total network power and blocking probability of the call admission control stage of the CCRRN is investigated. Our goal is to jointly optimize the bandwidth and power allocation such that the total transmission power in the CCRRN is minimized without compromising the Quality of Service (QoS) demands of the secondary users (SUs) and the interference constraint thresholds of the primary users (PUs) in the primary networks. The mathematical model and convex optimization problem with the aim of minimizing the total transmission power of the CCRRN was formulated. The resulting optimization problem was solved in the standard computer based numerical optimization solver package CONOPT in MATLAB/TOMLAB environment. Simulation results obtained is compared the equal-bandwidth optimal power allocation scheme.

Keywords- Cognitive radio Networks, Convex optimization, Cooperative relay networks, Transmit power minimization

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1 INTRODUCTION

Cognitive radio (CR) technology is regarded as a disruptive technology with potential to dynamically and efficiently exploit the under-utilized wireless radio spectrum resources. The prevailing wireless radio spectrum allocation is generally based on static command and control spectrum licensing paradigm (Zhu, Ying, and Feng, 2020). A major challenge in multi-user wireless networks is the efficient allocation of radio resources within the wireless networks Radio resources such as bandwidth and power control has been broadly researched (Nazir, Sabah, Sarwar, Yaseen and Jurcut, 2021; Zahid, Azmat, Khalid and Zahoor, 2019). However, the combined allocation of power and bandwidth has not received extensive attention.

The simultaneous optimization of power and bandwidth allocations among the multi-user nodes is an efficient way to optimize the networks performance of cooperative network. In this work, we study the combine optimization of bandwidth and power allocations with the goal to minimize the total transmission power in cooperative relay cognitive radio networks, while maintaining the integrity of the Quality of Service (QoS), the multi-users targeted transmission rates in secondary networks and the interference constraint thresholds of the primary users (Pus) in the primary networks.

Over the years, three major models of primary networks' spectrum sharing by the CR networks (secondary networks) have been proposed. These are interweaved (Awin, Abdel-Raheem, and Tepe, 2019), overlay (Liang, Ng, and Hanzo, 2017) and underlay (Cao, and Tellambura, 2015). The underlay spectrum sharing model enables secondary users (SUs) to access licensed radio spectrum bands of primary users (PUs) without carrying out spectrum sensing. Thus, SUs activities on PUs licensed spectrum bands are subjected to the constraint that accumulated interference from all SU nodes must not exceed tolerable interference threshold of the PUs. This constraint is usually referred to as interference threshold or temperature limit (Park, Jang and Lee, 2016). In this paper, the underlay spectrum access model is considered. The underlay spectrum access allows non license users to transmitted on the licensed spectrum simultaneously with the licensed or primary users, provide the non-licensed users do not cause any harmful interference to the licensed users. The underlay spectrum access does not require the complex sensing technique and hence it is simpler to implement in wireless communications.

Cooperative communication is another innovative technique that can significantly increase transmission reliability and capacity and also improve outage probability and network system performance in wireless communication networks (Bayrakdar, and Bayrakdar, 2015). In cooperative communication relay nodes are employed to re-transmit or forward the transmission source nodes messages or signals to the targeted transmission destination nodes. The prospect of integrating CR with cooperative communication features has garnered a lot of research interest as a promising solution for enhanced radio transmission capacity and spectrum utilization. Three main relaying strategies can be found in literature, Amplify and Forward (AF), Decode and Forward (DF) and Compress and Forward (CF)

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(Biyanwilage, Gunawardana and Liyanapathirana, 2014). The minimization of the transmission power is an important network issue in one-way DF relaying wireless networks.

In this paper, we focus on the investigation of the total transmission power minimization problem for a half-duplex one-way dual-hop DF cooperative cognitive radio relay communication network. We study the joint optimization of bandwidth and power allocations with the goal to minimize the total transmission power in cooperative relay cognitive radio networks, such that the QoS or the multi-users targeted transmission rates in secondary networks and the interference constraint thresholds of the PUs in the primary networks are not violated.

The rest of the paper is organized as follows: Section 2 provides a review of the related work. The system model of the proposed joint optimal resource allocation (COPBA) scheme is presented in Section 3, while the mathematical models of the analysis of the proposed scheme is provided in Section 4. Section 5 presents and discusses the results of the simulations. Finally, Section 6 concludes the paper. In the next section, we introduce the system model for the COPBA scheme. The COPBA scheme minimizes the total power consumption and blocking probability without degrading the minimum required rates of users in the wireless networks.

2 RELATED WORK

Generally, for wireless networks, rate maximization problems are more feasible than the power minimization (PM) problems. This high feasibility in PM is normally due to its rate constraints (Pan, *et al.*, 2014). In the works of Zou, Ganji, and Jafarkhani (2020) power minimization in non-orthogonal multiple access (NOMA) networks with cooperative asynchronous communication under targeted rate QoS constraints was investigated. A half-duplex cooperative asynchronous non-orthogonal multiple access NOMA(C-ANOMA) framework with a user with better channel quality relaying for a user with poorer channel quality is developed. To investigate the balanced trade-off between the power consumption of the base station and that of the relay, a weighted sum power minimization problem under QoS constraints was formulated. Numerical results showed that the C-ANOMA system has better power consumption performance than the C-NOMA system under the same QoS requirement constraint.

Yang, *et al.* (2018) investigated the problems of sum power minimization and sum-rate maximization for multi-cell networks with non-orthogonal multiple access. A closed-form solution for the optimal allocation policy is derived for the sum power minimization using the standard interference function. However, to solve the non–convex sum rate maximization problem, firstly it is shown that the power allocation problem for a single cell is a convex problem. Thus, with the Karush-Kuhn–Tucker (K.K.T.) conditions the optimal power allocation for the users in a single cell is derived in closed form. It is shown that the proposed power control technique can be extended to Multiple Input Multiple Output (MIMO) systems.

The water-filling method is an optimal solution to power control problems in OFDMA-based cellular networks (Taskou and Rasti, 2017). For battery-constrained Internet of Things (IoT) devices, a critical performance metric for these devices is a measure of the consumption of resource power. He (2020) investigated margin-adaptive loading problem for networks with mixed power and QoS bounded constraints. The minimization problem for the total power consumed by the entire system, subject to the throughput and sum power constraints for each group of channels is formulated. Employing the geometric concepts, an algorithm named the group virtual bottom power water-filling (GVB-PWF) is proposed to solve the problem. The proposed GVB-PWF is found to outperform the popular primal-dual interior-point method in terms of power consumption with the same am computational complexity.

AliHemmati, ShahbazPanahi, and Dong (2015) studied the joint spectrum sharing and power allocation for a bidirectional two-way relay Orthogonal Frequency Division Multiplexing (OFDM) based network. A joint power allocation and network beam-forming problem is formulated. The goal of the joint power allocation and network beam-forming problem is to minimize the total transmit power of the network subject to the transceiver rate constraints. A two-step iterative method that leads to (at least) a local optimum solution by allowing the joint problem to be decoupled into two independent sub-problems is proposed.

Chitti and Speidel (2013) considered the problem of joint base station association and power allocation for sum-power minimization with QoS constraint for a multi-cell multi-user uplink. The joint resource allocation problem is formulated as a Mixed Integer Nonlinear Programming (MINLP) optimization problem. Instead of using the conventional iterative method, where the power allocation (PA) and base station association (BSA) are solved alternately with one of them fixed, the author transformed the problem into a simple nonlinear programming (NLP) problem and then proposed the use of primal-dual infeasible-interior-point method (IIPM). Unlike the iterative method, the IIPM solves the joint PA and BSA problems simultaneously thus reducing it to a single-stage problem.

Very little work has been done to investigate the multi-user minimum rate requirement constraints for Cooperative Cognitive Radio Relay Network (CCRRN) power minimization, hence the motivation of this study. The main contributions of this paper are summarized as follows: firstly, we construct the multi-relays CCRRN based on the dual-hop model. Secondly, the closed-form achievable rate capacity for the dual-hop cooperative cognitive relay network is derived over a Rayleigh fading channel. Thirdly, the convex optimization analytical framework is presented. The sum power minimization problem is formulated, subject to the minimum QoS transmission rate constraints, with interference threshold or temperature limits, and available bandwidth constraints. Finally, we simulate the joint optimization scheme to validate it can greatly improve the performance of CCRRN.

3 SYSTEM MODEL

For the sum power minimization system model, we consider a multi-user multi-relay dual-hop wireless cooperative cognitive radio relay network as shown in Fig1. The CCRRN wireless network consists of Ncognitive source-destination pair nodes (S_i, D_i), $i \in \{1,2,3,\dots,N-1,N\}$. A source-destination pair $(S_i, D_i)$is defined as a user. The users are uniformly distributed in the network. We assume that all the communication pairs are assigned disjoint frequency channels and hence do not interfere with one another. For the one-way cooperative relaying, there are Mcognitive relay nodes R_k such that $k \in \{1,2,3,\dots,M-1,M\}$ and a primary user receiver PU within the CCRRN. Each user is assigned at most one relay node. The wireless network radio channels experience independent and frequency-selective Rayleigh fading. The channel model takes care of multipath, path-loss, and shadowing. The path-loss gain$p_l$is defined as $p_l = h^{-\varepsilon}$ where $h$is the distance between the transmitter and the receiver in each transmission phase and εdenotes the path loss exponent, which depends on the radio propagation environment.

All the channel links are subjected to path-loss and the Rayleigh fading effects. The channel gain,G, of the network consists of the integral sum effects of path-loss gain p_l, fading, and shadowing in the network. The noise power in the channel varies linearly with the channel bandwidth. The power spectral density (PSD) of additive white Gaussian noise (AWGN) is flat over all the frequencies with a constant value denoted by N_0. The relays are pre-assigned to a set of user nodes in the CCRRN with no direct link existing between source and destination nodes.

The black continuous arrows in Figure 1. Indicate the transmission from the source nodes to the relay nodes (first transmission time slot), while the red broken arrows indicate the transmission from the relay nodes to the destination nodes (second transmission phase)

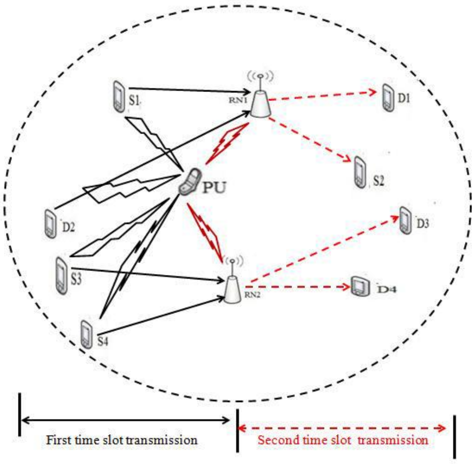

Fig.1: Network system model

3.1 UPLINK TRANSMISSION

LetP_S^idenote the transmit power of the i^{th}user source node and $B_S^i$is the available channel bandwidth of thei^{th}user source node. The achievable rate $R_{SR_k}^i$of the i^{th}user in the uplink transmission or first transmission time slot at the k^{th}relay node is determined as follows:

$$R_{SR_k}^i = B_S^i \, log(1 + \frac{P_S^i G_{SR_k}^i}{N_{P_S^i R_k}}) \qquad (1)$$

where $\frac{P_S^i G_{SR_k}^i}{N_{P_S^i R_k}}$is the received signal to noise ratio (SNR) on the i^{th}source to the k^{th}relay node link and $G_{SR_k}^i$is the channel gain of the i^{th}source to thek^{th}relay node link. The AWGN power over the channel bandwidth$B_S^i$is given by$N_{P_S^i R_k}$.

3.2 DOWNLINK TRANSMISSION

Let P_R^i denote transmit power of the k^{th} relay node for forwarding received message signal from the i^{th}source node and $B_{R_k}^i$is the available channel bandwidth at k^{th}relay node for forwarding received message signal received from the i^{th}source node. The achievable rate $R_{R_k D_i}^i$at i^{th}destination node via k^{th} relay in the downlink transmission or second transmission time slot is

$$R_{R_k D_i}^i = B_{R_k}^i \, log(1 + \frac{P_R^i G_{R_k D_i}^i}{N_{P_{R_k} D_i}}) \qquad (2)$$

where $\frac{P_R^i G_{R_k D_i}^i}{N_{P_{R_k} D_i}}$is the received signal to noise ratio (SNR) on the k^{th}relay node to the i^{th}destination node link.

The channel gain of thek^{th}relay node to thei^{th}destination node link is denoted by$G_{R_k D_i}^i$. The AWGN power over the bandwidth channel $B_{R_k}^i$is given by$N_{P_{R_k} D_i}$. The maximum achievable rate of the dual hopi^{th}Source-destination link user capacity is given by,

$$R_{SD}^i = \min\{R_{SR_k}^i, R_{R_k D_i}^i\} \qquad (3)$$

4 MATHEMATICAL MODEL

In this section, the mathematical model of the power minimization problem is presented.

4.1 PROBLEM FORMULATION: SUM POWER MINIMIZATION

It is crucial to jointly allocate the network bandwidth and transmit power resources to minimize the network resource consumption total network transmission power using optimization tools, while ensuring that the demanded user transmission ratesR_{min}^ior users' QoS constraints are not violated. Therefore, our goal is to jointly optimize bandwidth and power allocations in the dual-hop CCRRN in order to minimize the total network transmission power subject to the users' QoS constraints, the allowable interference constraints of the PU networks and total available bandwidth constraints at both the cognitive source and relay nodes. The total power minimization (PM) problem for the network can be formulated mathematically as:

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$$
\begin{aligned}
&PM: \min_{|P_S^i, P_R^i, B_S^i, B_{R_k}^i|} \sum_{i=1}^{N} P_S^i + P_{R_k}^i \\
&s.t: \\
&C1: R_{\min_{SR}}^i - R^i \leq 0 < \forall i \in N \\
&C2: R_{\min_{RD}}^i - R^i \leq 0 < \forall i \in N \\
&C3: \sum_{i=1}^{N} P_S^i \alpha^i \leq I^{th} \\
&C4: \sum_{i=1}^{N} P_R^i \alpha^k \leq I_{R_k}^{th}, \quad \forall k \in M \\
&C5: \sum_{i=1}^{N} P_S^i \leq P_{S_k}^T \qquad\qquad (4) \\
&C6: \sum_{i=1}^{N} P_R^i \leq P_{R_k}^T, \quad \forall k \in M \\
&C7: \sum_{i=1}^{N} B_S^i \leq B, \\
&C8: \sum_{k=1}^{M} \sum_{i=1}^{N} B_{R_k}^i \leq B, \\
&C9: P_S^i, P_R^i, B_S^i, B_{R_k}^i \geq 0, \ \forall i \in N, \forall k \in M
\end{aligned}
$$

The sum of $P_S^i$and P_R^i gives the network total transmission power. This serves as the objective function of network for the optimization problem formulation to be minimized. The constraint *C1* is the uplink targets minimum rate constraint during the first transmission time slot. It ensures the target minimum rate or QoS$R_{min\rightleftarrows RS}^i$ of the i^{th} user is not violated. The constraint *C2* is the downlink target minimum rate constraint of user i^{th} QoS during the second transmission time slot. The constraint *C3* is the interference constraint at source nodes during the uplink transmission slot. $\alpha^i$is the interference link gain between the i^{th}source node and the PU receiver, while $I^{th}$is the total allowable interference threshold by the PU receiver. The constraint *C4*is the interference constraint at relay nodes during the downlink transmission time slot. α^k is the interference link gain between the k^{th} relay node and the PU receiver, while $I_{R_k}^{th}$ is the total allowable interference threshold by the PU receiver from the R_k relay node. The constraint C5 is the multi-user source nodes power constraint during the uplink transmission time slot. The constraint *C6* is the multi-relay nodes power constraint during the downlink transmission time slot.

The constraint *C7* is the bandwidth constraint during the uplink transmission time slot. The constraint *C8* is the bandwidth constraint during the downlink transmission time slot. The constraint *C9* ensures that the decision variables of the optimizing problem are non-negative, since, it is physically meaningless to have negative transmission power or bandwidth allocation.

Proposition 1: Given the optimal bandwidth allocation in uplink transmission time slot $B_S^{i*}$and the optimal bandwidth allocation for the downlink transmission slot $B_{R_k}^{i*}$,thus, according to the water-filling algorithm, the analytical expressions for the optimal power allocation sub-problem for the source nodes in uplink transmission time slotP_S^{i*}, and the optimal power allocation sub-problem for the relay nodes for the downlink transmission time slot,P_R^{i*} are:

$$P_S^{i*} = \left[\frac{\lambda_1^i B_S^{i*}}{\nu_1 \alpha^i + \Lambda_1 - 1} - \frac{1}{\xi}\right]^+ \qquad (5)$$

$$P_R^{i*} = \left[\frac{\lambda_2^i B_{R_k}^{i*}}{\nu_{k2} \alpha_{R_k}^i + \Lambda_{k2} - 1} - \frac{1}{\tau}\right]^+ \qquad (6)$$

where $[x]^+ \underline{\Delta}\, max(x, 0), \xi = \frac{G_{SR_k}^i}{B_S^{i*} N_0}, \tau = \frac{G_{R_k D_i}^i}{B_{R_k}^{i*} N_0}$.

While λ_1^i, ν_1 and $\Lambda_1$are the Lagrange multipliers for the uplink transmission rate QoS constraint*C1,* the source nodes interference constraint *C3* and the source nodes power transmission constraint *C5*in the uplink transmission time slots, respectively. Alsoλ_2^i, ν_{k2} and $\Lambda_{k2}$are the Lagrange multipliers for the downlink transmission QoS constraint *C2,* the relay nodes interference constraint *C4* and the relay nodes power transmission constraint *C6*in the downlink transmission time slots, respectively.

Due to space limitation, the proofs of equations (5) and (6) are omitted in this paper. Equations (5) and (6) are the water-filling optimal solutions derived from the K.K.T. optimality conditions for power allocation in PM. In Section 5, the performance of our proposed combined optimal power and bandwidth allocation (COPBA) scheme is evaluated and compared with the traditional equal bandwidth and optimal power allocation (EBA) scheme.

5 NUMERICAL RESULTS AND DISCUSSION

This section presents the results of performance evaluation of our proposed COPBA scheme. The computer-based numerical optimization solver package-CONOPT implemented in MATLAB/TOMLAB software environment is used to solve the optimization problem. We compare the performance of the proposed schemes with the EBA scheme (Baccelli, F. and Kalamkar, S., *2020)* where channels are allocated uniformly to cognitive users. The EBA scheme is less computationally intensive, the results performance proved to be less efficient. The metrics considered in this study are network total power and network access blocking probability for call admission control. For a given random channel realization, the access network blocking probability is defined as the probability that the demanded rate capacity requirement conditions for all users in the CCRRN cannot be guaranteed. As indicated in the previous sections, different network variables can affect the CCRRN's total transmission power and the user network access blocking probability performances. Such network variables include the user's minimum required rate, the primary users' network interference threshold and total available bandwidth. The effects of each of these network variables on the network total transmission power and blocking probability are investigated. This study considers a CCRRN with six muti-user links (source and destination pair nodes) and three relays. The source and destination nodes are randomly distributed within a network dimensional range of (0, 0) and (16, 16). Each relay is pre-assigned to two user links, with the relays located at the positions (8, 2), (8, 8) and (8, 14) within the network. To achieve different instances of random channel realizations, all results presented here are averaged over 1,000 independent simulation runs. The complete simulation parameters are given in Table 1.

Table1. Simulation parameters

Parameter	Value
B	25MHz
P_S^T	1kW
$P_{R_k}^T$	5kW
I^{th}	0.1 W
I_k^{th}	0.1W
R_{min}^i	0.5Mbps
M	3
N	6
σ^2	1
ϵ	3

5.1 Effect of Minimum Required Rate on Network Total Transmission Power

Figure 2 shows total transmit power required by the overall network as a function of varying required minimum user rates. It can be observed that COPBA outperforms EBA significantly when the targeted user required rate is higher. The joint optimization of power and bandwidth becomes more significant at higher user target rates and thus yields larger performance gain. Hence, the COPBA scheme provides lower network total transmission power consumption than EBA, as it allows less transmission interference to the PUs' networks. However, when the target rate is low, the joint optimization is less effective and COPBA performance reduces and matches that of the EBA. The COPBA provides a maximum performance gain of 41.34% and an average performance gain of about 29.25% over that of the EBA scheme.

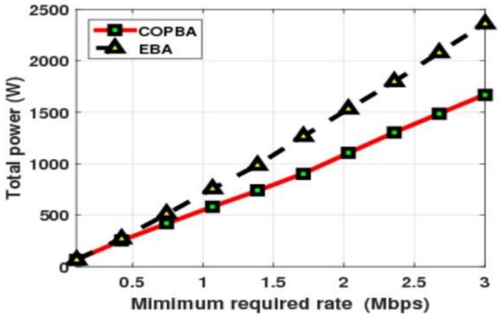

Fig. 2: Network total power vs minimum required rate

5.2 Effect of Interference Threshold on Network Total Transmission Power

The performance evaluation of the impact of varying total interference threshold on the network total power consumption of the CCRRN system is presented in Figure 3. The result depicts that the network total power consumption of the CCRRN increases for both schemes with higher interference threshold allocation. This follows from the fact that as the interference threshold restriction is increasingly relaxed, higher transmission rate can be achieved within the network by increasing the transmission power of the secondary users' network without interfering with the primary users. Therefore, the CCRRN is able to exploit such increase in interference threshold. This implies that the CCRRN can meet more of the required SUs' QoS without violating the interference thresholds of the PU's

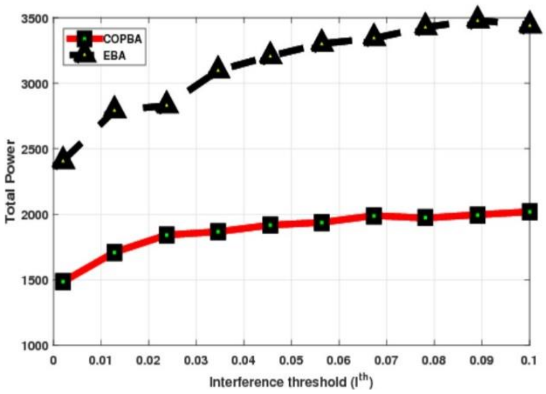

Fig. 3: Network total transmission power vs interference threshold

In addition, the network total power consumption of COPBA scheme is lower than EBA scheme for all interference thresholds. Also, COPBA total power consumption remains relatively stable as the primary network interference threshold is increased compared to the EBA scheme. The performance evaluation result presented in Figure 3 shows a maximum of 42.74% performance gain of COPBA over EBA and COPBA performs better than EBA with an average performance gain of 39.36%.

5.3 Effect of Minimum Required Rate on Blocking Probability

Figure 4 depicts the network access blocking probability trend with increasing minimum required rate capacity of the users in CCRRN. This indicates that, as users increase their minimum required rates, the probability of the user's minimum required rates will not satisfy increases. Therefore, the probability that user being denied access into the network increases. From Figure 4, COPBA achieves an average performance gain of about 18.51% over that of the EBA scheme and a maximum performance gain of 24.77%.

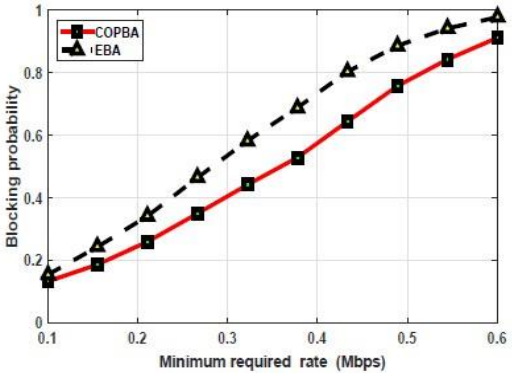

Fig. 4: Blocking probability vs minimum required rate

5.4 EFFECT OF INTERFERENCE THRESHOLD ON BLOCKING PROBABILITY

Fig. 5 shows the network access blocking probability versus the primary users' network interference threshold. It is seen that the COPBA has meagre performance over the conventional EBA for all interference threshold values, and the improvement is more profound when the interference threshold is increased. This indicated that an increasing number of users with higher capacity rate requirements can be granted access into CCRRN using the COPBA scheme. The COPBA achieves an average performance gain of about 4.97% over than that of the EBA scheme and a maximum performance gain of 7.87%

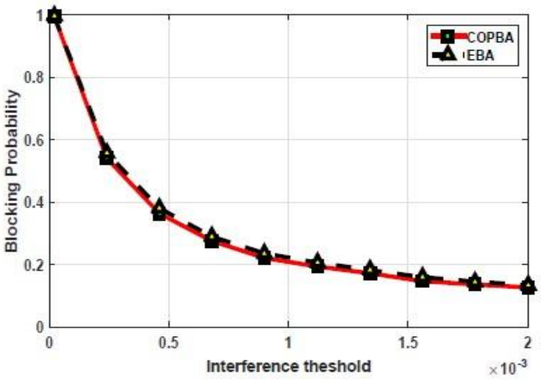

Fig. 5: Blocking probability vs inference threshold

5.5 EFFECT OF BANDWIDTH ON BLOCKING PROBABILITY

Finally, in Fig. 6, the effect of varying available bandwidth on CCRRN is investigated. The investigation revealed an observed general decreasing in blocking probability for both schemes as the available bandwidth increases. This means that as the available bandwidth to the CCRRN increases more SUs are granted access to the network. Usually, as available bandwidth increases, the channel capacity rate region increases, as more bits can be transmitted at an assigned power allocation. Therefore, the probability of the CCRRN not meeting the required rate capacity of all users decreases. Furthermore, it can be seen from Figure 6, that the COPBA provides lower network access blocking than EBA, hence the COPBA scheme provides more users with granted network access for any available bandwidth than the EBA scheme. The performance gain of COPBA scheme over EBA decreases fairly as the available bandwidth increases. The COPBA achieves an average performance gain of about 3.51% over that of the EBA scheme and a maximum performance gain of 9.19%.

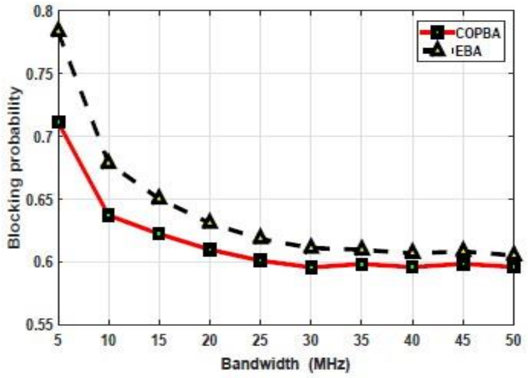

Fig. 6: Blocking probability vs available bandwidth

6 CONCLUSION

In this paper, we formulated the optimization problem to minimize network total transmission power consumption and network access blocking probability for call admission control, and provided the analytical optimal power allocation solutions to the power allocation sub-problem of the source and relay nodes in a cognitive radio network with cognitive cooperative communications. An analytical framework for achievable rate over Rayleigh fading channel was presented. We formulated total transmission power consumption minimization problem under relevant constraints and proposed a COPBA scheme for efficient allocation of power and bandwidth resources, and minimization of the network's total transmission power and blocking probability for call admission control.

The proposed COPBA scheme was compared to the conventional EBA scheme in terms of the network total transmission power consumption and network access blocking probability for varying user minimum required rates, PU network interference thresholds, and available bandwidths. The numerical results reveal that the system performance metrics under COPBA scheme have significant performance gains or improvements over the EBA scheme. From the average performance gain index, it is observed that increase in PUs network interference threshold has more performance impact on the network total power consumption than the minimum required rate of the users. Similarly, it is noted that variation in the SUs minimum required rate has the most performance impact on the network access blocking probability while the variation in total available bandwidth has the least performance impact.

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